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RELATION BETWEEN SAND GRAINS ON RECLAIMED LAND OF SAND COAST AND WIND VELOCITY

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16. Abstract

This report discusses the relation between wind force and sand grains, dealing with one aspect of a method for computing the number of days on which there is a movement of sand grains on the ground.

Both wind drag and critical wind velocity play a role in the acceleration of sand grains.

The angle of inclination of a sand dune is investigated by analogy with motion on an inclined plane.

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RELATION BETWEEN SAND GRAINS ON RECLAIMED LAND OF SAND COAST AND WIND VELOCITY (PRELIMINARY REPORT)

T. Chigusa and M. Akiba

Chapter 1. Introduction

Sand dune formations due to the deposition of coastal drift sand are seen in parts of our country's Pacific coastline and the Japan Sea coastline. /31*

When left ot nature, sand dunes sometimes drift and invade inland areas to turn arable land and forrested terrain into wasteland. Furthermore, the movement of sand dunes often results in the blockage of estuaries which leads to the shifting of the river mouths and alteration of the drainage situation to affect the drainage of cultivated areas upstream. Consequently, those engaged in agriculture must carry out coastal sand arrestation work in order to protect their land.

But reliance on coastal sand arrestation work is a passive approach. We are convinced that for the purpose of the reclamation of snad coasts, it is also neceesary to devise a method for the aggressive approach of utilizing sand dune formations to promote the extension of sandy coastal terrain into the sean so that the rapid expansion of usable land and the protection of reclaimed land can be achieved at the same time.

An example of the above approach is the reclaimed sand coast by the village of Ikeshinden, Ogasa County, Shizuoka Prefecture. Under the guidance of Professor Tanaka and Engineer Yamakita, the writers have been surveying this reclaimed land. Not having reached the stage of publishing the completed study yet, the writers would nevertheless like to present a portion of their study in the present issue in the form of a partial

*Numbers in margin indicate pagination in foreign text.

preliminary report for the eventual publication. The portion in question, which concerns the relation between wind force and sand grains, deals with one aspect of the method for computing the number of days on which there is a movement of sand grains on the ground, an area which has not been completely explored in the past, as well as the approximate wind velocity. It is hoped that this method may be of use in the utilization of wind force for the forward extension of sand coasts and the leveling of projected reclamation areas.

This subject will be discussed briefly in the next section, but it is to our regret that werwere unable to present the material on the basis of adequate investigation results for certain reasons. We therefore hope that there will be another opportunity for publishing a study which will not only rectify some of the inadequacies bur also deal with other easpects. Due to their limited knowledge, the writers have not seen equ equations which describe the relation between wind velocity and sand grains. In spite of their incompetence, the writers have attempted to formulate experimental equations and are publishing them in their still incomplete state. The writers will be honored to receive criticisms from the esteemed readers.

Chapter 2. Wind Velocity and Wind Force Capable of Conveying Sand Grains /32

[Translator's note: it is noted that the title for Chapter 2 above is different from the title given on the first page].

The movement of sand grains is based on single grains rather than on groups of grains. It is often related to specific gravity and size of the grains as well as their frictional force and cohesive force. At the same time, the movement is affected by wind velocity, wind direction and other factors. The specific gravity of sand varies according to its nature, but it is often in the vicinity of 2.6 for sand on the seacoast whose main component is quartz. In sand dunes, most of the sand grains belong to the quartz group, feldspar group, amphibole group, pyroxene group or the mica group, and their specific gravities usually exceed 2.5 with some exceptions. Although the sizes of the sand grains vary according to the locale, they seem to have more or less a constant value on beaches with sand dunes. According to Dr. Moroto, sand grains of diameters of 1.0 mm to 0.25 mm comprise the majority in our country, while Mr. Gerhardt asserts that in Germany the size range is from 0/1 mm to 2.0 mm with grains from 1.0 mm to 0.2 mm being the most common.

The frictional force of sand varies according to the properties of the constituents, but it has been recognized from past experiments that the coefficient of friction of dry sand is about 0.7. It can thus be assumed that the angle of respose is also more or less constant. With dry sand, the angle of repose is about 30°. The sand at Ikeshinden village also shows angles ranging from 30° to 36°.

The cohesive force of sand grains varies widely not only according to the nature of the sand, but also according to the presence or absence as well as the quantity of moisture. When the sand is completely dry, the force is almost zero while the coefficient of friction is equal to the tangent of the angle of repose. According to Mr. Leygue's report, the values are as follows.

	Coeff. of frict.	Angle of repose	Cohesive force (lb/ft^2)
Dry sand	0.7	35	1.47
Moist sand	0.85	40	8.28
Supermoist sand	1.70	59	1.30

It is assumed that even supermoist refers to a condition far removed from the state of saturation.

As far as the wind velocity is concerned, it is greatly influenced by the locale and the season. Nevertheless, the mean wind velocity for a given locale in a given season is more or less constant so that it is possible also to estimate the number of days on which there is high enough wind velocity to move the sand grains from meteorological survey data accumulated over a long period of time. Similarly, wind direction also tends to be relatively regular and constant for a given locale and a given season.

In the case of Ikeshinden village, which the writers are in the process of surveying, a great deal of inconveniences was experienced in the investigation due to the lack of such meteorological survey data. The only alternative was to use the records from Hamamatsu Meteorological Station several miles away for reference. With the establishment of a meteorological station for the Arable Land Dpeartment of the Shizuoka Prefectural Government this summer, we are confidant that every convenience will be provided for research in the future.

1. Critical Wind Velocity for Conveying Sand Grains

Let us consider for calculation the magnitude of force in the instant dry sand grains start their motion due to the wind force.

1. Force required for sand grain motion

Since sand grains in actuality have a large variety of shapes and properties, it would inevitably appear unreasonable /33
to consider them as uniform, but for the purpose of obtaining rough, approximate values it would be relatively feasible as long as it id done according to the observation of a superior technician.

Considering a sand grain as a sphere and letting r represent the average radius, the force in the instant this single grain is conveyed can be sought by

$$F=\frac{4}{3}\mu\rho\pi r^3 w \tag{1}$$

where

	μ	is the coefficient of friction of sand grain
	ρ	is the specific gravity of same
	π	is the circular constant
	r	is the radius of sphere (m)
	w	is the weight of unit volume of water (kg)

Next, when the beach sand from Ikeshinden village was subjected to selective analysis by means of the beaker method, the result turned out to be the same as what would have been obtained by sieve analysis. The reason for this is that when the sample was treated with ammonia, those smaller than 0.1 mm were in such a small quantity that there was no need to conduct analysis by precipitation.

Sand Grains at Ikeshinden Village
(20 grain sample)

Specific gravity 2.67

Grain diameter (mm)	over 1.0	over 0.5	over 0.1	under 0.1
Weight of grains (g)	0.01	1.22	18.58	0.19
Percentage (%)	0.05	6.1	92.2	0.95

Therefore, it would be possible to start the formation of sand dunes on the beach if sand grains of 0.1-0.5 mm could be put in motion. Accordingly, the force required for moving the sand grain by overcoming only the frictional force can be calculated from the equation above. It should be noted that the value of μ would vary considerably depending on whether the sand grain undergoes a rotational motion or a sliding motion. If it is a rotational motion, a small force would suffice.

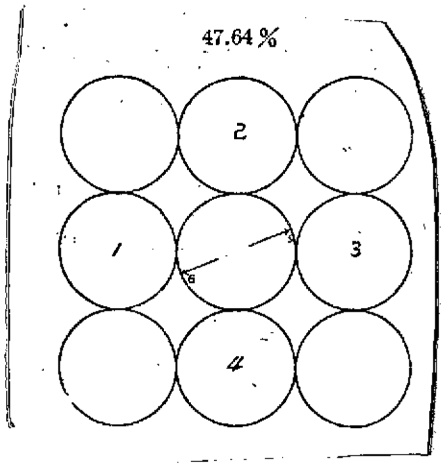


Fig. 1.

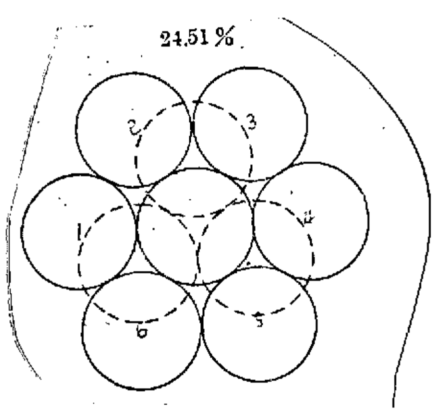


Fig. 2.

However, even if it is assumed that equation (1) is applicable to the case of a sand grain sliding over a plane surface composed of sand grains similar to it in nature, a large force in addition /34 to this force would be required in actuality since the surface would be undulating rather than plane. With respect to the surface of the sand with which the wind collides directly, a calculative expression would be difficult to formulate since the surface is a collection of grains of different sizes. A trial calculation will nevertheless be attempted by setting up the following assumption. Assuming that the sand grains are of a uniform size, the gap percentage within a fixed volume would be 47.64% to 24.51% although the possible arrangements of the grains are manifold. Using figures to illustrate this, the start of the motion would occur sooner in the case of the arrangement of Fig. 1 compared to the case of Fig. 2, while the grains in Fig. 2 are in the position of being required to climb over the grains in front of them in order to go into motion, so that the force for starting their motion would be greater than in the case of Fig. 1.

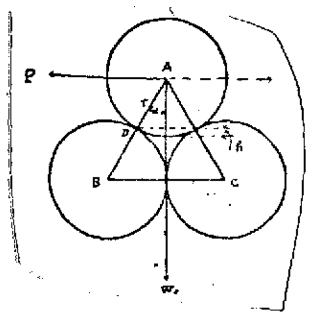


Fig. 3.

In Fig. 3, when grain A of radius r starts its motion caused by force P exerted in the direction of the arrow, the moment around point D would be

$$Pr\cos\alpha = W_s r\sin\alpha$$

where W_s is the weight of sand grain and W_s ...砂粒子の重さ

and generally,

$$P = W_s \tan\alpha$$
$$P = {}^4/_3\,\rho\pi r^3 w \tan\alpha \qquad (2)$$

In the case of Fig. 2 and Fig. 3, we get $\angle ABC = 60°$, $\alpha = 30°$ so that equation (2) becomes

$$P = 0.58 \times {}^4/_3\,\rho\pi r^3 w \qquad (2_1)$$

When the arrangement of the grains is studied with a magnifying lens, a considerable number of grains which are standing out and protruding are observed, but most of them do not form the arrangements mentioned above as they are uneven in size and not spherical. Some examples are shown in Fig. 4.

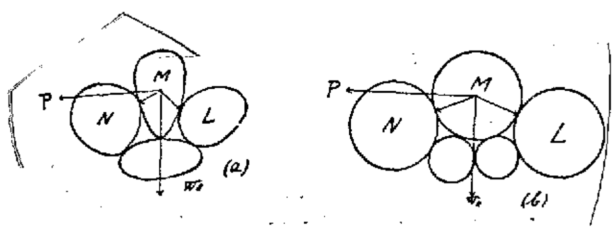


Fig. 4.

In cases such as (a), it is necessary to consider, apart from the above, resistance with respect to grain L, whereas in cases such as (b), angle α would be larger so that in practice α would have to be selected carefully. Looking at α from its limit value, it fluctuates around 30° on a sand dune so that with tan 30° = 0.58 as the basis k' in k' x 0.58 would supposedly be around 1. This point requires further research and investigation in the future.

Therefore, if angle α cannot be determined or if it is inaccurate, there would be no value whatsoever in applying the equation to practical uses. P is obtained in the manner of

$$P = {}^4\!/_3\, \rho\pi r^3 w k' \tan 30^\circ = {}^4\!/_3 \times 0.58 k' \rho\pi r^3 w \qquad (2_2)$$

In addition, it is necessary to take into consideration the case of collision between the sand grains, but by and large, it would seem possible to compute P fairly correctly if (F + P) is obtained from the first two equations and k' is determined by taking the extent of variation of the coarseness-fineness ratio and the forms of the grains into consideration. Thus,

$$F + P = {}^4\!/_3\, \mu\rho\pi r^3 w + {}^4\!/_3\, \rho\pi r^3 w \tan\alpha = {}^4\!/_3\, \rho\pi r^3 w(\mu + \tan\alpha) \qquad (3)$$ /35

or

$$F + P = {}^4\!/_3\, \rho\pi r^3 w(\mu + 0.58k') \qquad (3_1)$$

2. Wind drag and critical wind velocity

We have so far been considering the subject solely from the aspect of the sand grains. Let us now study them in terms of their correlation with the wind velocity. However, since the writers' knowledge regarding past studies of this aspect is limited only to findings concerning the rēlation between large objects and wind velocity, their intention is to continue their research into the case of such small objects as sand grains. On this occasion, results already obtained will be adopted for convenience's sake.

An object which is in motion in the air is exposed mainly to two kinds of resistances, namely the frictional drag (Reibungswiderstand) and the form drag (Formwiderstand). The former is caused by the surface of the object and the force which obstructs it, while the latter is caused by the form of the object. Generally speaking, the wind force drag (W) of an object directly facing the wind direction is

$$W = C_w . A . q$$

where A is the area of object directly facing wind direction

C_w is the coefficient which takes a value from tabulated Figure 5.

q is the obstructive force equal to $\gamma/2g\, V^2\ kg/m^2$

γ is the weight of air at the temperature of 15°C, barometric pressure 760 mm and medium humidity, and is 1.22 kg/m^3.

Under these circumstances, $q \doteqdot 1/16\, V^2$ so that

$$W = C_w A\, \gamma/2g\, V^2$$

and when

$$A = \pi r^2 \text{ とする時は}$$

$$W = C_w \pi r^2\, \gamma/2g\, V^2 \qquad (4)$$

Basically, air drag is affected mostly by the air movement around the object and the viscosity of air. Although the effect of the former is proportional to the velocity only in its ifrst power, the force exterted by the latter on the object is considered proportional to the velocity raised to the second power. For this reason, equation (4) was adopted. The variation in C_w according to the form of the object is shown in tabulated Fig. 5. This was taken from Hütte I. If the sand grain is approximately spherical, $C_w \doteqdot 0.5,\ \gamma/2g = 1/16$ and

$$W = 0.5/16\, \pi r^2 V^2 \qquad (4_1)$$

In the instant that the sand grain is about to start its motion, we get

$$W-(F+P)=0 \tag{5}$$

$$\therefore \quad C_w \pi r^2 \gamma / 2g \; V^2 = 4/3 \, \rho \pi r^3 w (\mu + \tan \alpha)$$

$$V = \sqrt{8g/3C_w \gamma \; \rho r w (\mu + \tan \alpha)} \tag{6}$$

Expressng r in meter form and w in kilogram form, we get /36

$$V = 146 \sqrt{1/C_w \; r \rho (\mu + \tan \alpha)} \tag{6_1}$$

and putting $\mu = \tan \varphi_r, \qquad \tan \alpha = k \cdot \tan \varphi_r$

$$V = 146 \sqrt{1/C_w \; \rho r (1+k) \tan \varphi_r} \tag{7}$$

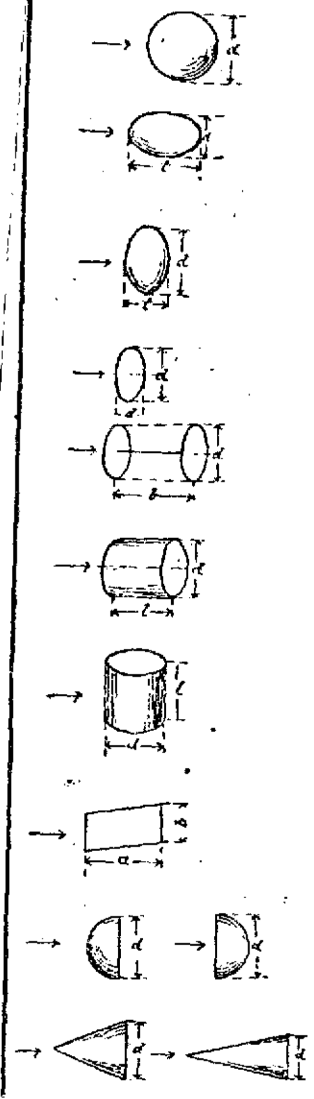
In equation (7), C_w and k vary widely according to the size, form and the arrangement of the grains, but since it is /37
difficult both to define them theoretically and to determine them experimentally and individually with respect to the sand grains, they are combined as

$$\sqrt{1/C_w (1+k)} = K \tag{8}$$

and (7):

$$V = 146 K \sqrt{\rho r \tan \varphi_r}$$

$$V = 146 K \sqrt{\mu \rho r} \tag{9}$$



		$C_w = \frac{W}{q}$
sphere ν = kinematic viscosity	$\frac{vd}{\nu} > 2.5,10^5$ $2.10^4 < \frac{vd}{\nu} 1.5,10^5$	0.22 0.47
Ellipsoid extending horizontally	$\frac{vd}{\nu} > 10^5$	0.05 bis 0.1
Ellipsoid extending vertically	$vd/\nu > 5.5,10^5$ $vd/\nu < 4.5,10^5$	0.2 0.6
Disc	$l/d = 1$	1.11
Parallel discs with interval ℓ	$l/d =$ 1 1.5 2 3	0.93 0.78 1.04 1.52
Perpendicular to base of cylinder	$l/d =$ 1 2 4 7	0.91 0.85 0.87 0.99
Perpendicular to side of cylinder	$l/d =$ 1 2 5 10 40 ∞	0.63 0.68 0.74 0.82 0.98 1.20
Rectangle	$a/d =$ 1 2 4 10 18 ∞	1.10 1.15 1.19 1.29 1.40 2.01
Semisphere (without base)		0.34 1.33
Circular cone	Vertical angle 60° 30°	0.51 0.34

Fig. 5.

Also, putting 146K = C

$$V = C\sqrt{\mu\rho r} \tag{9$_1$}$$

Therefore, the critical wind velocity would be proportional to the square roots of the coefficient of friction, specific gravity and radius in each case.

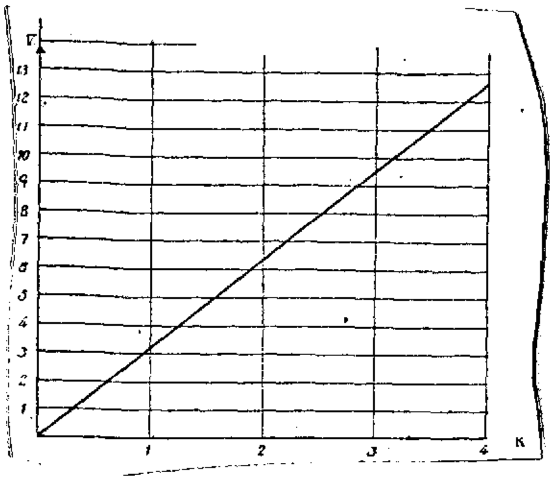


Fig. 6. Relation between V and K when:

$r = 1/4$mm
$\mu = 0.7$
$\rho = 2.6$

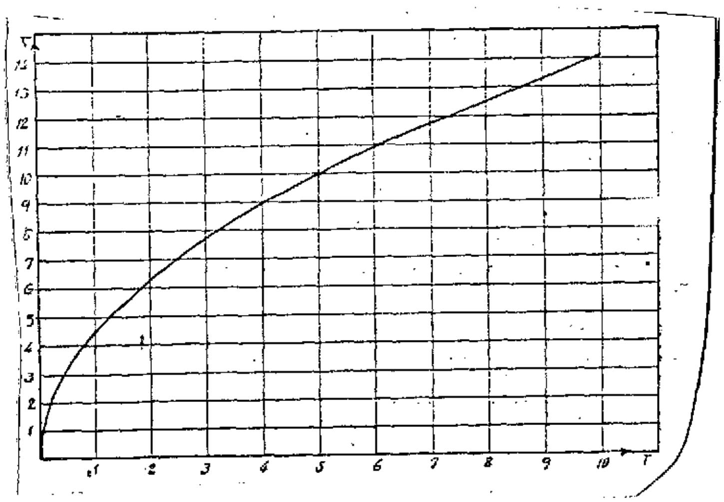


Fig. 7. Relation between $V(m)$ and $r(1/10)$ when $V = 146\kappa\sqrt{\mu\rho r}$, and $\mu = 0.7$, $\rho = 2.6$ and $k = 2.25$.

2. Relation between Velocity of Sand Grain and Wind Velocity

Since the velocity obtained from equation (5) is a critical velocity, it cannot sustain the motion of the sand grain. In order for the sand grain to maintain its motion, it requires a force capable of accelerating it. For this, the equation

$$W-(F+P)=p \tag{10}$$

must hold valid. In other words, if the grain was to start its motion with critical velocity, it would have to come to rest in the next instant. Therefore, if a constant acceleration is caused by the exertion of force p, the sand grain is also able to maintain its motion with a constant velocity.

In other words, the wind velocity V_W and the sand grain velocity V_S have a relationship of inequality which is to say

$$V_S \leq V_W$$ /38

The definition of the relation between these two are sought next. Letting a be the acceleration and m be the mass of the sand grain in this instance,

$$\begin{aligned} p &= am \\ m &= (4/3\,\rho\pi w r^3)/g \\ p &= 4a\rho w\pi r^3/3g \end{aligned}$$

In terms of unit time, we get

$$\begin{aligned} V_s &= 1/2\,a \\ V_s &= 3gp/8\rho w\pi r^3 \\ p &= 8\rho w\pi r^3 V_s/3g \end{aligned} \tag{11}$$

If the drag with respect to the wind velocity V_W is sought from equation (4), we get

$$W = C_w \pi r^2 \gamma/2g\; V_w^2$$

In this instance, we should get $V < V_W$, but this relation is not necessarily valid when the motion is rotational.

From equation (10) we get

$$\begin{aligned} C_w\pi r^2\gamma/2g\; V_w^2 - 4/3\,\rho\pi r^3 w(\mu+\tan\alpha) &= 8\rho w\pi r^3 V_s/3g \\ V_s &= 3g[\gamma/2g\,C_w V_w^2 - 4/3\,\rho\pi r^3 w(\mu+\tan\alpha)]/8\rho w r \end{aligned} \tag{12}$$

Using tan 30° as the standard, we get

$$V_s = 3g[\gamma/2g\,C_w V_w^2 - 4/3\,\rho\pi r^3 w(\mu+0.58k')]/8\rho w r \tag{12_1}$$

Since the relation between V_S and V_W is clarified by this equation (12), it becomes possible, as long as the movement of the sand grain within a given time period is known, to calculate the wind velocity, or to determine the movement of the sand from values recorded with an anemometer.

The above equation is applied to the case of sand moving along the ground, so that the equation has to be modified for th the case of sand flying through the air. On this point, it is hoped that a comparative study with observation values could be conducted sometime in the future.

One factor which must be noted at this point is that the velocity of wind carrying sand grains is somewhat lower than the velocity of wind which is not carrying them. For this reason, the relationship sought would not be valid for values recorded with an anemometer at a location where there is no flying sand unless they are first corrected.

The condition of movement was tested using sand grains collected form sand dunes at Ikeshinden village in July of this year. However, it only resulted in a rough glimpse of the outline of the condition due perhaps to an inadequacy in the testing device.

For the blower device an electric fan was used, and the velocity of the wind from it was measured with Robinson's anemometer. When the velocity was about 5.0 m the grains went into a slight motion, but the motion lacked promptness and appeared to involve only some of the grains. But even in this instance, there was a considerable amount of activity at the edge of an inclined plane.

Judging from this, it is supposed that in actuality sand grains on a sand dune probably do not move until the wind velocity /39 exceeds 5 m, which is to say the velocity of so-called gusts.

Obviously, the wind from an electric fan would differ somewhat from natural wind in that the former takes a rotational direction. The mean wind velocity in winter at the Hamamatsu Meteorological Station is around 5 m, but it is assumed that the wind velocity at Ikeshinden village would be greater since it is closer to the Pacific coastline.

3. Sand Grain Motion on Inclined Plane

The weight of each grain affects not only the movement of the sand grains along flat ground, but also movement on the inclined plane of sand dunes. Thus, greater wind velocity would be required for grains moving upward along an inclined plane than for grains on flat ground. If the wind velocity is insufficient so that it can only induce the initial motion, the sand grains would slide downward by their own weight. Since sand grains moving along the slope of a sand dune climb upward parallel to the slope, it is probably valid to assume that the wind direction in such a case is also approximately parallel to the incline.

Therefore, motion on an inclined plane is closely related to the angle of inclination of the sand dune. The force (F_1) capable of pushing sand grains up an inclined plane without undulations is represented by

$$F_1 = \mu W_s \cos\varphi + W_s \sin\varphi = 4/3\, \rho \pi r^3 w(\mu\cos\varphi + \sin\varphi) \qquad (10)$$

But since there are undulations in actuality, the force ($F_1 + P$) is generally required.

$$(F_1 + P) = 4/3\, \rho \pi r^3 w(\mu\cos\varphi + \sin\varphi + \tan\alpha) \qquad (11)$$

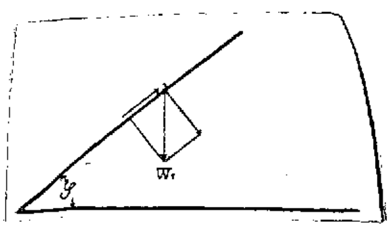


Fig. 8.

If the relation is sought in terms of the critical wind velocity (4):

$$W - (F_1 = P) = 0$$

$$C_w \pi r^2 \gamma/_{2g}\, V^2 = {}^4/_3\, \rho \pi r^3 w(\mu \cos\varphi + \sin\varphi + \tan\alpha)$$

$$V^2 = {}^4/_3\, {}^1/_{C_w}\, {}^{2g}/_{\gamma}\, \rho r w(\mu \cos\varphi + \sin\varphi + \tan\alpha)$$

Since usually $\frac{\gamma}{2g} = \frac{1}{16}$, we get

$$V = 146\sqrt{{}^1/_{C_w}\, \rho r(\mu \cos\varphi + \sin\varphi + 0.58k')} \qquad (12)$$

$$V = 146\sqrt{{}^1/_{C_w}\, \rho r(\mu \cos\varphi + \sin\varphi + \tan\alpha)} \qquad (12_2)$$

The slopes of the sand dunes vary in gradient from the windward side to the downwind side. The slopes on the windward side are never equal to the angle of repose of the sand since the wind force breaks the balance to reduce the gradient to less than this angle.

If the values

$$C_w = 0.5 \qquad \rho = 2.6 \qquad r = \frac{0.5^{\text{m.m.}}}{2}$$

$$\varphi = 12^\circ \qquad k' = 2 \qquad \mu = 0.7$$

are inserted into the above equation, we get

$$V = 6.5^{\text{m.}}$$

According to this, it would be possible to convey sand grains upward with a wind velocity not much different from that in the case of flat surface as long as the angle of inclination of the slope is around 12°. The relation between the velocity at which the sand grains travel upward along the sand dune

slope and the wind velocity in that instance may be obtained /40
by a method similar to before by using equations (6), (7), (8), (12) and equation (13) below. In other words

$$W-(F_1+P)=p_1 \tag{13}$$

Since the wind velocity obtained from equation (12) is the critical wind velocity with respect to the sand grain motion, the sand grains at this wind velocity would only move upward along the ground without exhibiting any vigorous motion. Therefore, a greater velocity would be required in order for vigorous motion to take place. Equation (13) must be utilized for this purpose. In such a case, the sand grains would not only travel along the ground, but also fly above the ground. But unlike the volvanic ashes invading the plains of Musashino in early spring, which fly at a very high altitude since the particles are find, the sand grains apparently remain within the range of 2 to 3 m above the ground.

The writers intend to conduct a comparison between the equations presented in this dissertation, and observation data and experimental results on another occasion so that these equations can be corrected.